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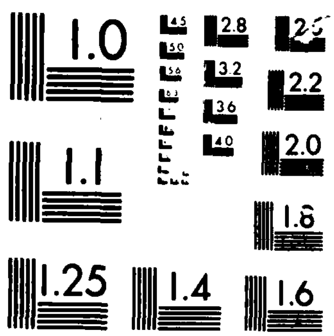
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SIGNAL ESTIMATION, SCATTERING THEORY AND INTERPOLATION PROBLEMS IN ONE AND TWO DIMENSIONS

FINAL REPORT

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FINAL REPORT

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    - J.M. Cioffi
    - T. Citron
    - Dr. I. Koltracht
    - S. Rao
    - S. Pombra
    - V. Balakrishnan

1 Work Completed

During the last three years we feel we have been fortunate to make several significant contributions, some of them in conjunction with long and short term visitors supported by this contract. We have been able to unify many past results in this area. Due to their fundamental nature and their wide applicability, most of our results reach across several topics. Drs. Lev-Ari, Bruckstein, Wax and Rao have completed their theses during the contracting period and have written a large number of publications.

The best overview of our research is provided by the list of publications describing the research supported at least in part by ARO.

In reference to the list of publications, the prefix P denotes published journal papers, C denotes published conference papers, A denotes accepted papers, and R denotes papers under review.

We shall briefly organize and review them here under four major headings:

1. Inverse Scattering Theory
2. VLSI and Parallel Architectures in Signal Processing
3. Adaptive Identification and Signal Processing
4. Stochastic System Modeling and Realization.

1.1 Inverse Scattering Theory

The recent period has seen a culmination of our work in inverse scattering theory. We have arrived at a satisfactory and simple understanding of the inverse scattering problem. A key to this has been a formulation in terms of transmission lines, which has shown that an algorithm due to I.Schur (1917) for testing analytic functions for boundedness is the most natural way to solve one-dimensional inverse problems. We have shown that various differential methods for inverse scattering are related to nonlinear evolution equations of the Riccati-type and, in the discrete case,to compositions of linear fractional transformations. Furthermore, it was found that the inverse scattering methodology could be applied to several other problems e.g. partial realizations. Finally the effect of noisy scattering data on the quality of the recovery of medium parameters and approximate methods of inversion using separation of overlapping echoes have been also extensively studied. The results are reported in papers P-9, P-15, A-7, A-9, A-10, R-9, C-6, C-7, C-10, C-12, C-13, C-19.

A thesis by A.M. Bruckstein made several major contributions to this area and abstract (of this thesis and of others cited below) is appended to this report.

1.2 VLSI and Parallel Architectures in Signal Processing

The Ph.D theses of Sailesh Rao and Todd Citron (to be submitted shortly) made major contributions to this area.

We have obtained exciting results on a new class of numerically stable, cascade, orthogonal digital filters that are well suited for VLSI implementation.

We have identified a class of algorithms called Regular Iterative Algorithms which can be systematically implemented on processor arrays with local interconnections. We have also shown that algorithms implementable on systolic arrays form a sub-class of these algorithms.

Another application has been to a new algorithm for decoding BCH error correcting codes, and more generally for the evaluation of the gcd of two polynomials. The new algorithm is much better suited to parallel VLSI implementations than currently known methods.

Publications in this area were P-4, P-11, P-13, C-10, C-11, C-18, C-23

1.3 Adaptive Identification and Signal Processing

Our development of new estimation algorithm also led to several results in system identification and signal processing. Applications to Communication Systems have been extensively studied. We have also obtained several results on Recursive-Least-Squares identification and estimation. Adaptive Filtering algorithms with automatic gain control were also obtained.

This activity is illustrated by papers P-6, P-7, P-12, P-17, P-18, R-10, C-8, C-9, C-14, C-28, C-31

A thesis by J.M. Cioffi was completed.

1.4 Stochastic System Modeling and Realization

Proper modeling of a stochastic system can lead to better understanding of the phenomenon and properly selected models can simplify associated estimation(filtering, prediction and smoothing) problems. Several results on factorization of structured matrices were also obtained.

This work was largely carried out by Dr. H. Lev-Ari.

Publications in this area were P-1, P-2, P-3, P-15, P-19, A-2, A-4, A-5, R-4, R-5, R-6, C-13, C-29

ARO

Published Journal Papers

P-1 I. Gohberg, T. Kailath and I. Koltracht, "Linear Complexity Algorithms for Semiseparable Matrices," **Journal Integral Equations and Operator Theory**, Vol. 8, pp. 779-804,December 1985.

P-2 T. Kailath and H. Lev-Ari, "On Mappings Between Covariance Matrices and Physical Systems," in *Contemporary Mathematics*, ed. B. Datta, Amer. Math. Socy., Vol. 47, pp. 241-252, Providence, R.I., 1985.

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P-11 T. Kailath, "Signal Processing in the VLSI Era," in *Modern Signal Processing and VLSI*, pp. 5-24, ed. by S. Y. Kung, H. Whitehouse and T. Kailath, Prentice-Hall, 1985.

P-12 J. M. Cioffi and T. Kailath, "An Efficient Exact-Least-Squares Fractionally Spaced Equalizer Using Intersymbol Interpolation," *IEEE Trans. Communications*, Vol SAC-2, no. 5, pp. 743-756, September 1984.

P-13 S. R. Rao and T. Kailath, "Orthogonal Digital Filters for VLSI Implementations," *IEEE Trans. Circuits & Systems*, Vol. CAS-31, no. 11, pp. 933-945, November 1984.

P-14 M. Wax, T-J. Shan and T. Kailath, "Spatio-Temporal Spectral Analysis by Eigenstructure Methods," *IEEE Trans. ASSP*, Vol. ASSP-32, no. 4, pp. 817-827, August 1984.

P-15 P. Dewilde and H. Dym, "Lossless Inverse Scattering, Digital Filters, and Estimation Theory," *IEEE Trans. on Inform. Thy.*, vol. IT-30, no. 4, pp. 644-662, July 1984.

P-16 T. Kailath and M. Wax, "A Note on the Complementary Model of Weinert and Desai," *IEEE Trans. Autom. Contr.*, Vol. AC-29, no.6, pp. 551-552, June 1984.

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A-1 T. Kailath, "A Theorem of I. Schur and Its Impact on Modern Signal Processing," special issue, *Integral Equations and Operator Theory,* 1986.

A-2 I. Gohberg, T. Kailath and I. Koltracht, "A Note on Diagonal Innovation Matrices," *IEEE Trans. ASSP*.

A-3 H. Lev-Ari and T. Kailath, "Triangular Factorization of Structured Hermitian Matrices," *Integral Equations and Operator Theory*, special issue dedicated to I. Schur, December 1985.

A-4 M. Wax and T. Kailath, "Decentralized Processing in Passive Arrays," *IEEE Trans. ASSP*.

A-5 A. Bruckstein and T. Kailath, "Inverse Scattering for Discrete Transmission-Line Models," *SIAM Review*.

A-6 A. M. Bruckstein and T. Kailath, "Recursive Limited Memory Filtering and Scattering Theory," *IEEE Trans. Inform. Thy.*

A-7 A. Bruckstein and T. Kailath, "An Inverse Scattering Framework for Several Problems in Signal Processing," *ASSP Magazine*.

A-8 T. Kailath and I. Koltracht, "Matrices with Block Toeplitz Inverses," *Linear Algebra and Its Applications*.

A-9 A. M. Bruckstein, T. J. Shan and T. Kailath, "The Resolution of Overlapping Echoes," *IEEE Trans. ASSP*, February 1984.

A-10 A. Bruckstein and T. Kailath, "Some Matrix Factorization Identities for Discrete Inverse Scattering," *Linear Algebra and Its Applications*.

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R-1 R. Roy, A. Paulraj and T. Kailath, "ESPRIT -- A Subspace Rotation Approach to Estimation of Parameters of Cisoids in Noise," submitted *IEEE Trans. ASSP.*

R-2 R. Roy, A. Paulraj and T. Kailath, "ESPRIT -- A Subspace Rotation Approach to Estimation of Parameters of Cisoids in Noise," submitted *IEEE ISCS*, San Jose, CA, May 1986.

R-3 A. M. Bruckstein, T. J. Shan and T. Kailath, "A Time-Domain Signal Resolution Problem," submitted *ICASSP 86*, Tokyo, Japan.

R-4 I. Gohberg, T. Kailath and I. Koltracht, "Linear Complexity Parallel Algorithm for Discrete-Time Wiener Filters with Optimum Lag," submitted *IEEE Trans. ASSP.*

R-5 I. Gohberg, T. Kailath and I. Koltracht, "Efficient Solution of Linear Systems of Equations with Recursive Structure," submitted *Linear Algebra and Its Applications.*

R-6 I. Gohberg, T. Kailath and I. Koltracht, "A Note on Diagonal Innovation Matrices," submitted *IEEE Trans. ASSP.*

R-7 M. Wax and T. Kailath, "Novel Eigenstructure Methods for Parameter Estimation of Superimposed Signals," submitted *IEEE Trans. ASSP.*

R-8 M. Wax and T. Kailath, "Simultaneous Detection and Estimation of Superimposed Signals," submitted *IEEE Trans. IT.*

R-9 A. M. Bruckstein, I. Koltracht and T. Kailath, "Inverse Scattering with Noisy Data," submitted *SIAM J. on Scientific and Statistical Computing.*

R-10 G. Sutton and J. M. Cioffi, "An Efficient Least-Squares Solution to the Double-Talking Problem in the Voice-Type Echo Canceller," submitted *IEEE Trans. Communications.*

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C-1 D. Spielman, A. Paulraj and T. Kailath, "Performance Analysis of the MUSIC Algorithm," *ICASSP*, Tokyo, Japan, April 1986.

C-2 D. Spielman, A. Paulraj and T. Kailath, "Eigenstructure Approach to Directions-of-Arrival Estimation in IR Detector Arrays," *ICASSP*, Tokyo, Japan, April 1986.

C-3 T. J. Shan, A. Paulraj and T. Kailath, "On Smoothed Rank Profile Tests in Eigenstructure Approach to Directions-of-Arrival Estimation," *ICASSP*, Tokyo, Japan, April 1986.

C-4 R. Roy, A. Paulraj and T. Kailath, "Direction-of-Arrival Estimation by Subspace Rotation Meth . - ESPRIT," *ICASSP*, Tokyo, Japan, 1986.

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C-8 T. J. Shan and T. Kailath, "Adaptive Filtering Algorithms with Automatic Gain Control," *19th Asilomar Conference on Circuits, Systems and Computers*, pp. , Monterey, CA, November 6, 1985.

C-9 J. M. Cioffi and T. Kailath, "An Efficient RLS, Data-Driven Echo Canceller for Fast Initialization of Full-Duplex Transmission," *ICC 1985*, Chicago, ILL, June 1985. IBM Research Laboratory Tech. Rept. RJ 4598, San Jose, CA, February 1985.

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C-11 S. K. Rao and T. Kailath, "Digital Filtering in VLSI," *Proc. Twenty-Second Annual Allerton Conf. on Comm., Control & Computing*, pp. 1-10, Oct. 1984.

C-12 T. Kailath and A. M. Bruckstein, "Naimark Dilations, State-Space Generators and Transmission Lines," *9th Annual Inter'l. Conf. on Operator Thy.*, Timisoara, Romania, June 4-14, 1984.

C-13 T. Kailath, A. Bruckstein and D. Morgan, "Fast Matrix Factorization via Discrete Transmission Lines," American Math. Soc. Meeting, *Linear Algebra and Its Role in Systems Theory*, July, 1984. Abstract

C-14 J. M. Cioffi and T. Kailath, "An Efficient, Recursive-Least Squares, Fractionally Spaced Equalizer using Intersymbol Interpolation," *ICC'84*, Amsterdam, Holland, May 14-17, 1984.

C-15 M. Wax and T. Kailath, "Determining the Number of Signals by Akaike's Information Criterion," *ICASSP*, pp. 6.3.1-6.3.4, San Diego, CA, March 1984.

C-16 T. J. Shan and T. Kailath, "New Adaptive Processor for Coherent Signals and Interference" *ICASSP*, pp. 33.5.1-33.5.4, San Diego, CA, March 1984.

C-17 M. Wax and T. Kailath, "A New Approach to Decentralized Array Processing," *ICASSP*, pp. 40.7.1-40.7.4, San Diego, CA, March 1984.

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C-20 T. J. Shan, M. Wax and T. Kailath, "Spatial Smoothing Approach for Location Estimation of Coherent Sources," *17th Asilomar Conference on Circuits, Systems and Computers*, Monterey, CA, Oct. 1983.

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C-22 H. Lev-Ari and T. Kailath, "Spectral Analysis of Nonstationary Processes," *IEEE Inter'l. Symp. on Inform. Thy.*, St. Jovite, Quebec, Canada, Sept. 1983. Abstract.

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C-24 M. Wax and T. Kailath, "Determining the Number of Signals by Information Theoretic Criteria," *ASSP Spectrum Estimation Workshop II*, Tampa, FL, November 10-11, 1983.

C-25 T. J. Shan and T. Kailath, "Adaptive Beamforming for Coherent Signals and Interference," *ASSP Spectrum Estimation Workshop II*, Tampa, FL, November 10-11, 1983.

C-26 M. Wax, T-J. Shan and T. Kailath, "Covariance Eigenstructure Approach to Detection and Estimation by Passive Arrays," Pt. I: Direction-of-Arrial and Frequency Estimation of Multiple Narrowband Sources," *IEEE International Symp. on Inform Thy.* Canada, September 1983.

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C-28 J. M. Cioffi and T. Kailath, "Fast, Fixed-Order, Least-Squares Algorithms for Adaptive Filtering," *1983 ICASSP.* pp. 679-682, Boston, MA, April 1983.

C-29 M. Wax and T. Kailath, "Efficient Inversion of Doubly Block Toeplitz Matrix," *1983 ICASSP*, pp. 170-173, April 1983, Boston, MA.

C-30 M. Wax, T-J. Shan and T. Kailath, "Covriance Eigenstructure Approach to 2-D Harmonic Retrieval," *1983 ICASSP*, 891-894, April 1983, Boston, MA.

C-31 V. U. Reddy, T-J. Shan and T. Kailath, "Application of Modified Least-Square Algorithm to Adaptive Echo Cancellation," *1983 ICASSP*, pp. 53-56, April 1983, Boston, MA.

SCATTERING MODELS IN SIGNAL PROCESSING

A DISSERTATION

SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING

AND THE COMMITTEE ON GRADUATE STUDIES

OF STANFORD UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

by

Alfred Marcel Bruckstein

October 1984

SCATTERING MODELS IN SIGNAL PROCESSING

Alfred Marcel Bruckstein, Ph.D.

Stanford University, 1984

Wave propagation in a layered, one-dimensional, scattering medium is interpreted as a model for various signal processing algorithms. The computational methods for determining the propagated waves from the ones launched into the medium at boundaries and the changes in overall medium properties under cascading of scattering layers with given properties form the conceptual basis shared by many such algorithms.

In filtering of signals with given state-space models, the Hamiltonian formulation suggests that the estimates and the adjoint variables may be regarded as waves propagating in a medium extending in time, with local properties defined by the time varying signal model. Using this interpretation a new algorithm for limited-memory Kalman filtering is derived.

Physical scattering theory deals with the more general situation of infinite-dimensional vectors or time functions propagating in a medium that extends in space. In this, spatio-temporal setting, the structure of parametrized media may be adjusted to model a variety of objects, from a general linear system to nonuniform transmission-lines, geophysical layered-earth structures and wave-digital filters. Inverse problems, requiring the determination of medium properties from its response to a probing signal, are shown to be solvable, for a variety of

medium structures, by either layer-peeling or layer-adjoining algorithms. These recursive inverse scattering procedures, derived by simple causality arguments, are computationally efficient since, in some sense, they let the medium perform the inversion by itself and thus directly and fully exploit the structural information about it. When applied to various scattering structures, these inversion algorithms provide alternative methods of deconvolution, nested partial realization, geophysical prospecting, and synthesis of nonuniform transmission-lines and digital filters.

Causality and symmetry principles are shown to provide a unified derivation of the classical methods for solving inverse problems. These methods proceed via solutions of nested sets of integral (matrix) equations. In this context we make the connection to fast estimation/factorization algorithms, by showing that the recursive procedures derived in the literature exploit matrix structures to indirectly arrive at layer-adjoining algorithms. Some practical issues concerning inverse scattering with noisy data, and a new algorithm for inversion which combines noise propagation results with prior information on parameter profiles, are also analyzed.

Approved for publication:

By Thomas Kailath
For Major Department

By Gerald J. Lieberman
Dean of Graduate Studies & Research

NONSTATIONARY LATTICE-FILTER MODELING

by

Hanoch Lev-Ari

Technical Report

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ABSTRACT

The dissertation presents a general theory of constant-parameter modular lattice models for nonstationary, discrete-time, second-order processes. This theory spans a wide range of topics, beginning with the derivation of a canonical parametrization of nonstationary covariances, proceeding through covariance extension and interpolation problems, and culminating in the construction of lattice-form modeling and whitening filters.

The canonical parametrization of nonstationary covariances involves *Schur coefficients,* which coincide with the well-known reflection (or PARCOR) coefficients when the covariance is stationary, and the newly introduced *congruence coefficients,* which are necessary to complete the parametrization. The congruence coefficients also provide the time-varying gains of a tapped-delay-time realization of the whitening filter for the process. A constant-parameter realization of the same filter can be derived by combining a lattice filter structure with a tapped-delay-line, both with time-invariant gains. This configuration also provides a recursive relation for the congruence coefficients (namely, a generalized Levinson-Szegö recursion).

The tapped-delay-line part of the lattice-filter model can be eliminated for covariances that possess a newly defined property called *admissibility.* The parametrization of admissible covariances involves the Schur coefficients alone, in analogy to stationary covariances, which are completely characterized by their PARCOR coefficients. We derive an explicit expression for the congruence coefficients of admissible covariances in terms of the Schur coefficients. Admissibility also plays a central role in the derivation of Christoffel-Darboux-type formulas for inversion of covariances, and provides a convenient classification of all covariances into four basic types.

The construction of constant-parameter lattice models is made possible by developing a natural connection between the displacement structure property of a covariance matrix and Schur's test for positive semi-definiteness of matrices. We also extend the displacement structure property, thereby expanding the class of nonstationary covariances that possess a lattice-form model.

Several properties that are commonly associated with stationary covariances are shown to be exhibited also by certain nonstationary processes. In addition to constant-parameter lattice models and Schur-coefficient parametrization, which were already mentioned above, these include the minimum-phase property of whitening filters, the maximum-entropy property of finite-order interpolants, and the existence of (asymptotic) spectral density functions. In particular, we present a family of nonstationary covariances that possess *all* the properties mentioned above.

From a methodological point of view, the dissertation introduces a transform-domain approach, in contrast to the time-domain approach used in previous work on nonstationary lattice-filter modeling. Many of the new results in this dissertation have been stimulated by the transform-domain interpretation of known results. The simplicity of the transform-domain derivation of these new results exhibits the utility of our approach.

REGULAR ITERATIVE ALGORITHMS AND THEIR IMPLEMENTATIONS ON PROCESSOR ARRAYS

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ABSTRACT

This dissertation is about *Regular Iterative Algorithms*, their properties, their implementations on processor arrays and their applications. It is shown that there exists a sub-class of these Regular Iterative Algorithms that is isomorphic with *systolic/wavefront* arrays. Given an algorithm that belongs to this sub-class, certain procedures are devised for obtaining a variety of systolic array architectures for implementing the algorithm. Among the infinitely many such arrays that can be designed, some pointers are provided for making a rational choice, based on some objective criteria.

If the given Regular Iterative Algorithm is not necessarily in this sub-class, then some procedures are presented for determining asymptotic lower-bounds on the time required for executing the algorithm, and on the amount of storage necessary during the execution. Further, it is shown how one can derive processor array implementations of the algorithm which meet the predicted lower bounds. However, the resulting processor arrays are not systolic as per the definition used here, but can always be described as regular interconnections of *similar* processing elements, together with *register pipelines*, all operating in a globally synchronous fashion.

The procedures described for obtaining these lower-bounds and for designing an implementation of the algorithm, can be executed in constant time on some sequential *back-end* processor, independent of the number of computations in the Regular Iterative Algorithm. Furthermore, the processor arrays derived for implementing the algorithm can be simulated on a fixed torus-connected architecture, thus opening up the possibility of designing a compiler that takes as input a high-level description of the Regular Iterative Algorithm and outputs the program that must be repeatedly executed by each processor in such an architecture.

The usefulness of Regular Iterative Algorithms for various problems in signal processing, graph theory, numerical linear algebra and other scientific applications is also demonstrated in this thesis. In most cases, these Regular Iterative Algorithms can be derived by reformulating existing ones using some simple heuristic rules. For some problems, such as digital filtering and the problem of determining the transitive closure of a graph, it is shown to be advantageous to consider the problem afresh and synthesize Regular Iterative Algorithms for them, from first principles.

FAST TRANSVERSAL FILTERS

FOR

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FAST TRANSVERSAL FILTERS FOR COMMUNICATIONS APPLICATIONS

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ABSTRACT

Adaptive transversal filters have been proposed as solutions for many real-time linear-estimation problems in communications, such as channel equalization, echo cancellation and antenna-array beamforming. Recursive-Least-Squares (RLS) adaptive algorithms, which have been implemented in lattice as well as transversal-filter form, have been shown to exhibit excellent convergence and tracking properties in these same applications. However, these RLS algorithms have suffered from high computational requirements and/or poor numerical (limited-precision) performance in comparison to the widely used, but slower-converging, stochastic-gradient or Least-Mean-Square (LMS) adaptive algorithms. In this dissertation, transversal filters are further examined in the solution of the RLS problem to render computational cost competitive with the LMS algorithms and to provide acceptable numerical performance for these real-time applications. These improvements are achieved while simultaneously maintaining complete compatibility with the widely-used stochastic-gradient (LMS) algorithms.

We present new Fast Transversal Filters (FTF) adaptive algorithms. The FTF algorithms reduce computation by a factor of at least two, and in many cases by more than an order of magnitude, in comparison to the most efficient, existing, RLS algorithms (thus, the name "Fast"). Further comparison reveals computational requirements of the FTF algorithms that range, depending on the application, from .5 to 3.5 times those of the slower-learning, stochastic-gradient algorithms. Various common windows are considered for the RLS criterion, and the FTF algorithms are extended to the so-called "covariance" windows, as well as to a more general window, by recursively propagating additional transversal filters. We also investigate and solve numerical-instability problems that arise both during initialization and during steady-state (real-time) operation of the algorithms. The solutions include modifications of the FTF algorithms to include soft-constraints on the performance criteria, rescue operations, and dynamic-range-increasing normalized (square-root) FTF algorithms. Conceptually, all improvements are attained through various uses of a single geometric formula that is a generalization of the Pythagorean Theorem.

Simulations are presented to verify the performance and improvements of the FTF algorithms. Specific results are presented for the applications of a fractionally spaced equalizer, a data-driven echo canceller, and a voice-type echo canceller.

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